Can Ultrahigh Energy Cosmic Rays Come from Gamma-Ray Bursts? II: Cosmic Rays Below the Ankle and Galactic GRB

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ABSTRACT

The maximum cosmic ray energy achievable by acceleration by a relativistic blast wave is derived. It is shown that forward shocks from long GRB in the interstellar medium are powerful enough to produce the Galactic cosmic-ray component just below the ankle at 4×10^{18}eV, as per an earlier suggestion (Levinson & Eichler 1993). It is further argued that, were extragalactic long GRBs responsible for the component *above* the ankle as well, the occasional Galactic GRB within the solar circle would contribute more than the observational limits on the outward flux from the solar circle, unless an avoidance scenario, such as intermittency and/or beaming, allows the present-day, local flux to be less than 10^{-3} of the average. Difficulties with these avoidance scenarios are noted.

Subject headings: Galaxy, cosmic rays, gamma-ray bursts

1. Introduction

The ultrahigh-energy (UHE) range of the cosmic-ray (CR) spectrum is generally broken into three parts: 1) the steeper knee-to-ankle segment ($\sim 10^{15.5}$ to $10^{18.6}$eV), 2) the flatter "trans-ankle" CR below the GZK cutoff ($10^{19.6}$ eV), 3) and trans-GZK CR. Trans-ankle CR are probably extragalactic, showing little anisotropy at $E \leq 10^{19.6}$ eV, and some anisotropy at $E \geq 10^{19.6}$ eV towards the local supercluster.

In this paper, we consider the hypothesis of sub-ankle UHECR origin from long GRB (Levinson & Eichler 1993; Wick et al. 2004; Calvez et al. 2010). We show that (a) Galactic

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γ-ray bursts (GRB) are sufficiently good accelerators and sufficiently powerful to account for sub-ankle UHECR, but that (b) the UHECR near-isotropy limits the current Galactic UHECR output per unit star-forming mass to a value far less than what is energetically required to account for trans-ankle extragalactic UHECR by extragalactic GRB. Conclusion (b) can be generalized to any hypothetical UHECR source whose rate density, like that of long GRB, is in proportion to star formation. This challenges any model in which such sources account for *all* UHECR.

Many past authors have proposed that GRB make the CR above 10^{19} eV, but for this energy range there remains the alternative hypothesis that they come from active galaxies (The Pierre AUGER Collaboration et al. 2010). Doubts remain that GRB could supply the highest-energy cosmic rays. The problems include disparity in the total energetics of each (Eichler et al. 2010, Part I, and references therein), adiabatic losses, which lower the maximum energy should the acceleration be in a compact region, and the isotropy problem. The isotropy problem, discussed here and in an accompanying paper (Part III), is basically that stars in the Milky Way are distributed anisotropically relative to the Earth. If they - or sources similarly distributed - were responsible for UHECR, the UHECR should also show anisotropy, the Galactic magnetic field notwithstanding. Part III studies in detail the propagation of CR from Galactic GRB and specifically compare with data the expected anisotropy, composition, and intermittency behavior.

2. Particle Acceleration in Outflows: A General Discussion

To be efficiently shock accelerated, a CR that has crossed the shock toward the upstream must be overtaken again by the shock of the order of $n \equiv \beta/\beta_S$ times, where β, the velocity of the particle in units of c, exceeds β_S, the velocity of the shock. If the shock moves at Lorentz factor Γ_S, then a CR that is overtaken by a spherical blast wave of age T at radius $R_S \sim \beta_S cT$ must have been deflected (by gyration or scattering) through an angle $\Delta\theta \gtrsim 1/\Gamma_S$, while residing upstream, within a time $\Delta t \sim R_S/\beta cn = \beta_S R_S/\beta^2 c$.[1] In other words, a necessary condition for efficient shock acceleration is that $\Delta\theta/\Delta t = ZeB/\gamma mc \geq \beta^2 c/(\beta_S R_S \Gamma_S)$. Defining the maximum kinetic energy E_{max} for convenience to be $\sim \beta_{max}^2 \gamma_{max} mc^2$, we may

[1]Here it is assumed that, whether the propagation is stochastic or scatter-free, each reorientation or reversal of direction must happen within a CR path length of order $\beta_S R_S/\beta$, as the cumulative time a CR spends within a gyroradius r_g of the shock is only $\sim R_S/\beta c$. This assumption may be controversial for scatter-free propagation in a perpendicular magnetic field, because there is no rigorous proof to our knowledge of impossibility of more prolonged trapping, but neither are we aware of any counterexample in view of systematic drift (see below).

write

$$E_{max} \lesssim Ze\,B\,\beta_S R_S\,\Gamma_S \tag{1}$$

which generalizes previous results for diffusive shock acceleration (DSA) [Eichler (1981), Forman and Drury (1983) and references therein], and for scatter-free shock drift, when $\Gamma_S \sim 1$.[2] Note that scatter-free gyration even in perpendicular shocks, though it gives a much thinner precursor than stochastic propagation, cannot in general confine a CR particle to a subrelativistic blast wave (e.g. a supernova remnant) in all three dimensions, for the particle would generally drift off to the side within a time $R_s/\beta c$ after gaining the potential difference $ZeB\beta_S R_S$ in energy. Also note that we have neglected adiabatic losses.

Random scattering, for a given magnetic-field amplitude, changes the CR's direction more slowly than undisturbed gyration and, for relativistic shocks, usually makes it harder for the shock to catch up with a particle. Therefore if turbulent magnetic field amplification (MFA) increases the field strength to a value B_{rms}, equation (1) should not be used with $B = B_{rms}$ if the coherent scattering angle is less than $1/\Gamma_S$, i.e. if the coherence length of the field l is less than r_g/Γ_S.

For random small deflections of $\delta\theta$, the mean free path λ is about $\beta c/D_{\theta\theta}$, where the angular diffusion coefficient, $D_{\theta\theta}$, is given by $D_{\theta\theta} = (\delta\theta)^2/\delta t \sim [ZeB_{rms}/\beta\gamma mc^2]^2 l^2/(l/\beta c) = r_g^{-2} l\beta c$, where $\delta t \sim l/\beta c$ is the scattering coherence time over which the particle scatters by an angle $\delta\theta$, l is the coherence length of the magnetic field, and r_g, in a turbulently enhanced magnetic field, is defined as $r_g \equiv \beta\gamma mc^2/ZeB_{rms}$. The condition for efficient acceleration is now $\overline{\Delta\theta^2} = D_{\theta\theta}\Delta t \geq 1/\Gamma_S^2$, or $r_g^2/l \sim \lambda \lesssim \beta_S R_S \Gamma_S^2/\beta$. Finally, we have

$$E_{max} \lesssim Ze\,B_{rms}\,[lR_S\beta_S\beta]^{\frac{1}{2}}\,\Gamma_S \tag{2}$$

which, for a given field strength, is less than the previous expression for E_{max} when $l \leq r_g/\Gamma_S$.

This expression for E_{max} implies that, if $l \leq r_g/\Gamma_S$, MFA raises E_{max} only if it raises the value of $B_{rms}^2 l$. Simply tangling the field on a small scale so that its strength varies as $1/l^\eta$, $\eta \leq 1/2$, does not raise E_{max}.

For a self-similar, energy-conserving relativistic blast wave in the interstellar medium

[2] Note that the expression $E_{max} = Ze\,B\,R_S$, often taken from figure 1 of Hillas (1984), is consistent with equation (1) only if β_s and Γ_s are both of order unity.

(Blandford & McKee 1976)

$$R_S \approx (17E/16\pi\rho c^2)^{1/3}\Gamma_S^{-2/3} \approx (6\times 10^{18}\ \mathrm{cm})\left(\frac{E_{54}}{n_0}\right)^{1/3}\Gamma_S^{-2/3}. \tag{3}$$

where the total energy of the blast is $10^{54}E_{54}$ ergs and the ambient nucleon density is $n_0\mathrm{cm}^{-3}$. This suggests, again taking the limit for $\Delta\theta/\Delta t$ as arising from coherent gyration, that the gyroradius of a maximally energetic escaped particle is

$$r_{g,max} \approx \Gamma_S R_S \approx (6\times 10^{18}\ \mathrm{cm})\left(\frac{E_{54}}{n_0}\right)^{1/3}\Gamma_S^{1/3}. \tag{4}$$

In the early stages of a powerful GRB blast wave, $0.1 \le E_{54} \le 10$, $\Gamma_S \sim 10^3$, while $10^{-2} \lesssim n_0 \lesssim 1$. Escaping particles, therefore, should obey $10^{18.5} \lesssim r_g \lesssim 10^{20.8}$ cm, and contribute to the Galactic CR component in the corresponding energy range. They should be represented in the flux we observe and in the quantity $\dot{w}_G$, which is defined below to be the CR power per unit baryon mass within the Galactic solar circle.

The range $10^{18.5}$ cm $\le r_g \le 10^{20.8}$ cm in the Galaxy corresponds to the energy range $10^{16}\ \ Z\,[B/10\mu G] \lesssim E \lesssim 10^{18.3}\ \ Z\,[B/10\mu G]$ eV, precisely the range, to within the uncertainties, of the "knee-to-ankle" portion of the CR spectrum, which is said to evade the capabilities of supernovae. Relativistic blast waves in the Galaxy fill in this range nicely.

Ultrarelativistic shocks are likely to be quasiperpendicular in the frame of the shock, and, on these grounds, their ability to accelerate particles efficiently has been questioned. We agree that it is, *a priori*, a fair concern, but note that nonthermal spectra in GRB afterglows seem to indicate that shock acceleration works there just fine. The many ways to evade the arguments against shock acceleration in quasiperpendicular geometries are not the subject of this paper.

3. The CR power per unit baryon mass

If we were to suppose that the mechanism supplying the sub-ankle CR somehow extends well beyond the ankle, we would encounter the problem that the Galactic component of these CR would be highly anisotropic, assuming their source distribution would be concentrated inside the solar circle in the Galaxy, because their transport is no longer fully diffusive and includes many Lévy flights. This, in addition to the sharp change in spectral index at the ankle, is reason to suppose that Galactic GRB limit their output to CR below the ankle. Even in the sub-ankle range, the observational limits on anisotropy pose strong constraints on the models. Below, and in (Part III: Pohl & Eichler 2011), this is further quantified.

Let $f_{sc,b} M_{sc} = (2 \times 10^{44}\ \mathrm{g})\, f_{sc,b}$ be the total baryonic mass within the Solar circle, where $M_{sc} \sim 2 \times 10^{44}$g. Using the allsky UHECR integral flux $F[E_1, E_2]$ in energy interval $[E_1, E_2]$ (in units of EeV) implied by Auger, and assuming that the fluxes above the ankle are extragalactic and uniform in the cosmos, we find that the UHECR source power per unit baryon mass in the [4,40] range, $\dot{w}_{[4,40]}$, is

$$\dot{w}_{[4,40]} = \frac{F_{[4,40]}}{\lambda_{[4,40]}\, \Omega_B\, \rho_c} \approx (40\ \mathrm{erg\, g^{-1}\, yr^{-1}}) \left(\frac{\lambda_{[4,40]}}{\mathrm{Gpc}}\right)^{-1}, \tag{5}$$

where $F_{[4,40]} = 0.017\ \mathrm{erg/cm^2/yr}$ (Eichler et al. 2010; Abraham et al. 2010a), and the implied luminosity from within the Galaxy's solar sphere, $\dot{E}_{[4,40]}$, is

$$\dot{E}_{[4,40]} = \dot{w}_{[4,40],G}\, M_{sc}\, f_{sc,b} \approx (2.5 \times 10^{38}\ \mathrm{erg\, s^{-1}}) \left(\frac{\lambda_{[4,40]}}{\mathrm{Gpc}}\right)^{-1} f_s^{-1}\, f_{sc,b}, \tag{6}$$

Here $\lambda_{[E_1,E_2]}$ is the "horizon" range[3] of UHECR in the $[E_1, E_2]$ range, ($\lambda_{[4,40]} \sim 1$ Gpc), $\Omega_B \rho_c \approx 1.4 \times 10^{-31}\mathrm{g/cm^3}$ is the cosmic density in baryons, and $f_s = \dot{w}_{[4,40]}/\dot{w}_{[4,40,G]}$ is the ratio of the average UHECR source power per unit baryon mass to that in our Galaxy. To be precise, the subscript "G' denotes the Galactic value within the solar sphere. Because spiral galaxies like our own comprise about half the cosmic mass, with the other half in galaxies with less star formation and hence probably lower UHECR source power, one may estimate the value of f_s to be about 1/2 if UHECR sources are distributed in proportion to star formation.

On the other hand, if the solar system fairly samples the outward flux of cosmic rays within the energy range $[E_1, E_2]$ through the solar sphere, i.e., if the local flux equals the average over the solar sphere, then the inferred power is given by

$$\dot{E}_{[E_1,E_2]} = 4\pi\, F_{[E_1,E_2]}\, R_{sc}^2\, \bar{\beta}_{[E_1,E_2]} \equiv 4\pi\, R_{sc}^2 \int_{E_1}^{E_2} E\bar{\beta}(E) c f(E) dE \tag{7}$$

where $R_{sc} = 8$ kpc is the radius of the solar circle and $\bar{\beta}_{[E_1,E_2]}c$ is the average ratio of enthalpy flux [in the anticenter direction, defined to be $\mu \equiv \cos\theta = 1$], $\int_1^2 dE \int d\mu [E\mu f(E,\mu)]$ [where the integral runs from E_1 to E_2], to energy density $4\pi \int_1^2 dE[Ef(E)/c] \equiv 2\pi \int_1^2 dE \int d\mu[Ef(E,\mu)/c]$. It is measured directly for each energy bin with CR anisotropy measurements. The current experimental limits on $\bar{\beta}$ set by the Auger Observatory are, to 99% confidence, $\bar{\beta} \leq 0.004$ in

[3]The horizon range is shorter than the instantaneous range because the expansion of the universe enhances the losses both by adiabatic deceleration of the particles and a raising of the background photon energy density and the losses it causes in the past relative to the present.

the [0.4,4] EeV range and $\bar{\beta} \leq 0.025$ in the [4,40] EeV range (Abreu et al., 2011). Here we have used the facts that most of the energy flux is towards the low end of these ranges, where the limits on anisotropy are strongest, and that $\bar{\beta}$ is 1/3 of the first harmonic amplitude given by Abreu et al. (2011). Under this assumption, we obtain

$$\dot{E}_{[4,40]} = F_{[4,40]}\, 4\pi\, R_{sc}^2\, \bar{\beta}_{[4,40]} \lesssim 1 \times 10^{35}\ \mathrm{erg\,s^{-1}} \tag{8}$$

and correspondingly

$$\dot{E}_{[0.4,4]} = F_{[0.4,4]}\, 4\pi\, R_{sc}^2\, \bar{\beta}_{[0.4,4]} \lesssim 2 \times 10^{35}\ \mathrm{erg\,s^{-1}} \tag{9}$$

Equations (6) and (8), together with the constraints on $\bar{\beta}$ imply that

$$f_s = \frac{\dot{w}_{[4,40]}}{\dot{w}_{[4,40],G}} \gtrsim 2500\, f_{sc,b} \left(\frac{\lambda_{[4,40]}}{\mathrm{Gpc}}\right)^{-1} \tag{10}$$

Note that all UHECR sources that have a power scaling with star-forming mass, e.g. the hypernova scenario for long GRB, should have a high likelihood of being present in the Galaxy, i.e. $f_s < 1$. We conclude that if a) the sources of UHECR are fairly represented in our own Galaxy, and b) the solar-system location fairly samples these CR at present, then the hypothesis that such sources in other galaxies maintain an extragalactic flux at the observed level would be inconsistent with the observed CR flux. There would be more CR production within the solar circle than allowed by observation. This is a challenge to any theory of UHECR origin from long GRB.

4. Discussion

The limit on inferred source power per unit baryon mass required to sustain Galactic UHECR in the [4-40] EeV range that is imposed by the observed anisotropy limits is smaller, by more than 3 orders of magnitude, than what is required for an extragalactic origin, as calculated in Eichler et al. (2010), and it corresponds far better to the power per unit mass of gamma rays from GRB. This numerical coincidence fits the hypothesis of a GRB origin for the Galactic component of UHECR, without invoking a much larger unseen energy reservoir for GRB. In fact, it would allow a Galactic origin for UHECR above the ankle were it somehow possible to trap these CR within the Galaxy effectively enough to obey the isotropy constraint. It remains to be shown that applying the hypothesis of UHECR from Galactic GRB to subankle Galactic CRobeys the isotropy constraint, and this analysis is done in Part III (Pohl & Eichler 2011).

Although the discussion, for historical reasons, has used GRB as a standard for power production, it is independent of GRB. The highest-energy CRs, whatever their source, are surely extragalactic, and apparently produced with a higher power per unit (star forming) mass than that contributed by the matter within the Galactic solar sphere, given the observed limits of UHECR outflow from this sphere. This challenges any theory of their origin from matter and phenomena of the sort to be found within 10 kpc or so of the Galactic center.

We have considered several alternative possibilities. AGN are an obvious possibility, as they are not represented by our Galaxy, i.e. $\dot{w}/\dot{w}_G \gg 1$.

Another possibility is that the sources are white dwarfs or neutron-star mergers from binaries in a very extended halo, and that they spend very little of their time within the solar sphere. Conceivably this could include short GRB, although their total energy output in the cosmos is probably an order of magnitude less than even that of long GRB, so the question of total energetics would still loom large. On the other hand, short GRB, not being tied to the SFR, need not suffer the recent decline in rate relative to earlier epochs, and so could be an order of magnitude more common, relative to long bursts, at present than in earlier epochs. In any case, one would still have to check that the implied flux is below observed levels and of a suitable angular distribution. Why, for example, would there be correlation above the GZK cutoff with the local supercluster? If one is willing to attribute sub-GZK CR above the ankle to a different class of sources from those above the GZK cutoff, then short GRB in the Galactic halo may account for the former, provided they are distant enough to respect the strong limits on anisotropy.

In an effort to accommodate the hypothesis of a GRB origin for *all* UHECR, we have also considered the possibility that our present location does not fairly sample the UHECR exiting the solar sphere, and that the large UHECR output that would be necessary to supply all of the UHECR at energies where their flux would be extragalactic could then mostly evade the solar system. They conceivably could, for example, be blown out in jets that have avoided our location and/or with an intermittency that excluded the present epoch receiving a fair representation of the time average. If GRB blasts were to escort all their CR safely out of the Galaxy in narrow jets that avoid our location, there would be less of an anisotropy problem associated with a GRB origin for extragalactic UHECR. But this scenario would differ from the common view that GRB blasts slow down to subrelativistic Lorentz factors, spreading in angle, within the Galaxy. If the UHECR escape the jet, then according to equation 4, they probably get significantly deflected before escaping the Galaxy at large, and it is not obvious that they could remain sufficiently collimated to conform to an avoidance scenario. A single jet, if it leaks UHECR, contaminates the sky with a strongly anisotropic component at the energy range in which CR are strongly scattered by

the Galactic magnetic field, but not contained by the jet. If, on the other hand, the jet contains all the UHECR, then the latter suffer enormous adiabatic losses. The question is whether all but $\sim 10^{-3}$ of the UHECR can avoid leaking or escaping into the Galaxy at large and mixing with its CR population. This would appear to require a scenario in which CR at $\sim 10^{19}$eV would be extremely well confined to the shock (strong scattering) without suffering adiabatic losses and without being scattered out of the shock's path into the interstellar medium.

Intermittency may explain a low flux from Galactic long GRB, if the time between GRB per Milky-Way-type galaxy were more than $R_{sc}/(3c\bar{\beta}) \simeq 10^4/\bar{\beta}$ years, the escape time of CR from the Galaxy. The collimation of GRB jets to within several degrees however, which is now believed to be the case, suggests that GRB are as frequent as $10^{-7} f_b^{-1}$ per year per M_{sc}, where f_b is the beaming factor, believed to be of order $10^{-1.5}$ to 10^{-3}. Specifically, the local rate of GRB that we detect is $R = R_1$ Gpc^{-3} yr^{-1}, with $R_1 \sim 1$. The expected rate R_G within the Galaxy should then be

$$R_G \simeq (1.6 \cdot 10^{-9}\ \mathrm{yr}^{-1}) \frac{f_{sc,b}\, R_1}{f_b\, f_s\, \Omega_B} \simeq (2.5 \cdot 10^{-5}\ \mathrm{yr}^{-1})\, R_1\, f_{sc,b} \left(\frac{f_b}{10^{-2.5}}\right)^{-1} \left(\frac{f_s\, \Omega_B}{0.02}\right)^{-1}. \quad (11)$$

Given the near isotropy of UHECR, if a good fraction of them were produced within the solar circle, their escape time from the Galaxy, $R_{sc}/\bar{\beta}c$ would be larger than $1/R_G$, and there would necessarily be many Galactic GRB per escape time. Moreover, if the escape is exponential, more that 10 escape times would be necessary to clear all but 10^{-3} of the CR released by the GRB. These considerations suggest that supply intermittency from GRB is most plausible when $\bar{\beta} \sim 1$, but it is doubtful that the assumption of $\bar{\beta} \sim 1$ is consistent with the strong limits on anisotropy.

On the other hand, the original scenario of Levinson & Eichler (1993), in which Galactic GRB supply the Galactic CR component below the ankle, need not make significant energy demands on the GRB, because there is no constraint imposed on the required output per unit mass other than what the local Galactic flux dictates. Given the low anisotropy of UHECR, it is likely that those below the ankle are confined to the Galaxy for nearly 10^6 years, in which case the rate of GRB and their energy output are consistent with a CR production per GRB that is less than that of gamma radiation per GRB. This however, would be incompatible with the hypothesis that GRB produce UHECR above the ankle as well (Eichler et al. 2010).

While the low observed anisotropy eases the energy demands on sources of Galactic UHECR, it imposes a strong constraint of its own. It remains to be shown that sources of UHECR, if distributed as luminous stars in our Galaxy, indeed satisfy the constraint of low anisotropy. This question depends on the question of the mean free paths of UHECR, hence

on their composition, and is taken up in a companion paper (Pohl & Eichler 2011).

Here we have concluded that GRB are energetically sufficient to provide the sub-ankle Galactic CRs, given what is known about shock acceleration, relativistic blast waves, and GRB parameters. If the hypothesis of GRB origin for sub-ankle UHECR is true, it may have implications for the Galactic magnetic field and/or the distribution of those GRB.

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REFERENCES

Abraham, J., et al. 2010a, Phys. Lett. B, 685, 239

Abraham, J., et al. 2010b, Physical Review Letters, 104, 091101

Abreu, P, et al (Pierre Auger Colaboration), 2011, Astroparticle Physics 34, 627

Blandford, R. D., & McKee, C. F. 1976, Physics of Fluids, 19, 1130

Blümer, J., Engel, R., Hörandel, J. R. 2009, Progress in Particle and Nuclear Physics, 63, 293

Calvez, A., Kusenko, A., & Nagataki, S. 2010, Physical Review Letters, 105, 091101

Eichler, D. 1981, ApJ 244, 711

Eichler, D., Guetta,D. & Pohl, M. 2010, ApJ 722, 543

Forman, M. A. & Drury, L. O. 1983. Proceedings from the 18th International Cosmic Ray Conference, Bangalore, India, 22 August - 3 September, volume 2 (OG Sessions), p. 267

Hillas, M. , 1984, Ann. Reviews of Astr. and Ap., 22, 425

Levinson, A. & Eichler, D. 1993, ApJ 418, L386

The Pierre AUGER Collaboration, et al. 2010, Astroparticle Physics, 34, 314

Pohl, M., & Eichler, D. 2011, ApJ submitted (Paper III)

Vietri, M. 1995, ApJ 453, 883.

Waxman, E. 1995, Ph. Rev. Lett. 75, 386.

Wick, S. D., Dermer, C. D., and Atoyan, A., 2004, Astropart. Phys., 21, 125